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Understanding Transients: Needs from the Laboratory Astrophysics Community

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Abstract: A growing number of astrophysical transients are pushing astronomers to develop increasingly complex computational tools to model both radiation hydrodynamics and electron transport. Here we review the physics needs and simulation uncertainties associated with modeling these transients. Although this review will focus on theory and simulation aspects of this problem, we also review some experiments designed to study this physics.

Scientific Goals: Astrophysical transients are powered through both shock heating and energy deposition from electrons produced in the beta-decay of radioactive isotopes. Accurate modeling of these energy deposition mechanisms is critical to using observations of these transients to probe properties of these explosions, from understanding the true yields from the ejecta from neutron star merger events to studying the properties of supernova progenitors and the violent mass loss that precedes the supernova explosion. Astrophysicists are developing increasingly sophisticated physics modules to more accurately calculate this physics. Laboratory experiments are in a prime position to validate these new methods, ensuring the accuracy of these new methods.

Shock Heating: In the simplest supernova models, a spherically symmetric shock plows through a spherically symmetric star and surrounding wind profile. In this simplified picture, shock heating is limited to a forward shock and, because the shock decelerates, the subsequent reverse shock. Analytic solutions of this shock heating can be used to model a number of observed transient phenomena from shock breakout to superluminous supernovae. Unfortunately, the explosion is asymmetric and it plows through stellar/circumstellar media that harbor their own asymmetries. These asymmetries drive a complex series of shocks that cannot be solved by analytic solutions alone. Detailed radiation-hydrodynamics models are required to capture this evolution.

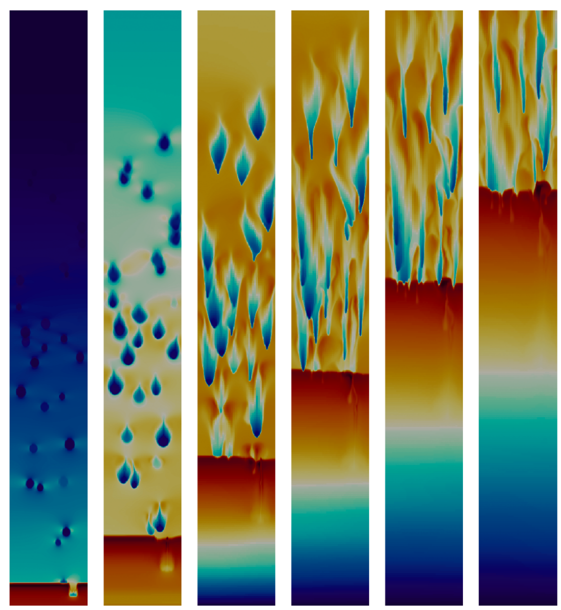

Figure 1: Time series of radiation-hydrodynamics simulation of a supernova shock interacting with turbulent wind medium. Shocks from these interactions reheat the supernova ejecta producing X-ray and UV emission seen in supernovae at early times. These calculations require detailed coupling of the radiation propagation with the hydrodynamic turbulence.

An example of this physics in an astrophysical transient is the early-time shock emergence in core-collapse supernovae. In most supernovae, the photon emission makes up only a fraction of the energy stored in the supernova blast wave. Turbulence in the massive stellar wind produces a clumpy wind medium. When the supernova blast wave drives through this clumpy wind medium, the resultant shocks from this interaction heat up the ejecta, converting the kinetic energy of the blast wave into bright X-ray and ultraviolet emission[1]. Figure 1 shows simulations using the LANL's radiation-hydrodynamics Cassio code[1-3]. Understanding how this shock and its radiation will interact with this clump (for example, does the radiation preheat the clump prior to a strong shock developing?) is critical in determining the exact strength of these shocks. Experiments that can validate the radiation-hydrodynamics coupling methods are critical to improving astrophysical calculations of this phenomena. This physics also plays a role in thermonuclear supernovae (interactions of the blast wave of the exploding star with its binary companion) and superluminous supernovae where extremely bright supernovae are produced when the energetic blastwave interacts with a shell of material from a mass-loss episode in stellar evolution (binary mass ejection, stellar pulsations).

At LANL, a suite of experiments has been developed to study this flow, developing and testing a temperature diagnostic to better measure the radiation flow across a boundary and through stochastic medium: COAX, Radishock, OuTi [4-6]. This temperature diagnostic has provided a strong constraint on the nature of the radiation flow, but much more work must be done to constrain the uncertainties in these experiments to probe the radiation-hydrodynamics methods developed at LANL.

Electron Heating: The other primary source of heating that drives the emission in astrophysical transients arises from the deposition of energy of energetic electrons produced in the beta decay of radioactive isotopes produced in the explosive engine behind these transients. Thermonuclear supernovae are powered by the decay of radioactive ^{56}Ni produced in the explosion. Energetic electrons produced in this decay deposit their energy as they scatter through the ejecta, ultimately heating the ejecta and powering the emission observed in these supernovae. This electron heating is important in a wide range of transient light-curves including the core-collapse explosion of Wolf-Rayet stars (type Ib/c supernovae) and the newly observed "kilonova" transient rising from the ejecta produced in the merger of neutron stars (in this latter case, the radioactive elements are heavy rapid neutron capture isotopes). Codes are being developed to improve the modeling of electron transport at higher fidelity. Even so, electron transport is modeled with simplified solutions using angle-integrated interaction cross-sections. In addition, electron transport will need to include the effects of the magnetic fields developed in the turbulent exploding medium.

Tools Required: Because this paper focuses on the validations needs for theory and not the design of upcoming experiments, we focus just on the theoretical tools in development to better model this physics. For shock heating, the key computational tools needed are improved radiation-hydrodynamics coupling models. Although higher-order transport schemes (e.g. implicit Monte Carlo and discrete ordinate methods such as S_N) are becoming increasingly common, the coupling of these schemes to hydrodynamics is still typically done through simplified operator-split methods and few methods incorporate transport schemes that leverage the sub-grid turbulence models in these hydrodynamics calculations. Methods to include this physics are currently under development and validation experiments are critical.

Transport methods for electrons range from fully-kinetic calculations (e.g. particle-in-cell) that include effects of these electrons on the magnetic fields to in-situ energy deposition, calculating only the energy deposited without even modeling the spatial disposition of this heating. Kinetic calculations are too computationally costly to model the full astrophysical event, but a number of new approaches are being proposed: reduced-order models, higher-order transport methods focusing on electron transport. For astrophysical transients, the most critical physics is probably the electron transport. Advances in electron transport require a better understanding of interaction cross-sections for the electrons. In addition to the cross-sections, the propagation through turbulent magnetic fields must also be included.

Scientific Impact: We have already discussed some of the astrophysical transients that require next-generation modeling. These phenomena have strong ties to upcoming NASA missions. For the early emission from supernovae, a number of satellites are being proposed that will observe the ultraviolet or X-ray emission from these early time outbursts. Our current understanding of this emission has been set by serendipitous observations from the Swift satellite. The UltraSAT mission has initial funding and will increase the number of observations of this emission (only in the ultraviolet)[]. The proposed SIBEX mission will increase the number of such observations by at least tenfold in both X-rays and ultraviolet (including spectra). Both ground- and space-based missions exist and are being developed to observed transients from neutron star mergers (counterparts to gravitational wave detections). Needless to say, time-domain and multi-messenger astronomy are one of the most active areas of research in astronomy and understanding the physics behind these transients is becoming increasingly critical.

Any experiments validating the physics behind these two important energy sources for astrophysical transients will also validate codes used in a number of other applications from inertial confinement fusion to space weather.

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